WIND TUNNEL TEST AND VIBRATION TEST FOR RATIONALIZATION STEEL BOX-GIRDER BRIDGE

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ABSTRACT

"Steel narrow-box-girder bridge" is rationalized about main structure of steel box-girder bride. Points of rationalization are following. The first, it is possible to reduce number of girder because slab span is widely by using durable slab such as composed slab of steel and concrete, or prestressed concrete slab. The second, cross beam and lateral bracing are leaved or simplified. The third, construction of box rib is simplified by being web space narrow.
Recently, steel narrow-box-girder bridge is increasing in Japan, because constructional cost and maintenance cost are economically compared with former steel box-girder bride. On the other hand, steel narrow-box-girder bridge has low frequency on torsion, because of its small torsion stiffness. So, one of the not cleared subjects of steel narrow-box-girder bridge is endurance for wind.
We have carried out wind tunnel test and vibration test for steel narrow-box-girder bridge to obtain characteristics of wind. We used second-dimensional scale down model supported springs in wind tunnel test, and used real steel narrow-box-girder bridge which max span is110 meter in vibration test. This paper reports results of these tests.

1. INTRODUCTION

A PC slab, steel-concrete composite slab or other durable slab is employed for steel road bridges from the viewpoint of cost reduction. By using these types of slabs, cross girders, lateral bracing or other transverse tie members can be simplified or omitted. Instances of employing such rationalized bridge types have increased in recent years. The steel narrow box-girder bridge, whose main girders have a box-shaped cross-section, is a rationalized bridge developed for use where there are curves or long spans (60 to 100 meters or so) in bridges and its track record in terms of construction is growing. One feature of the steel narrow box-girder bridge is that the number of longitudinal and cross ribs can be reduced by reducing the web distance. In this way, the structure inside the box is simplified and the number of construction components is substantially reduced (Figure 1).

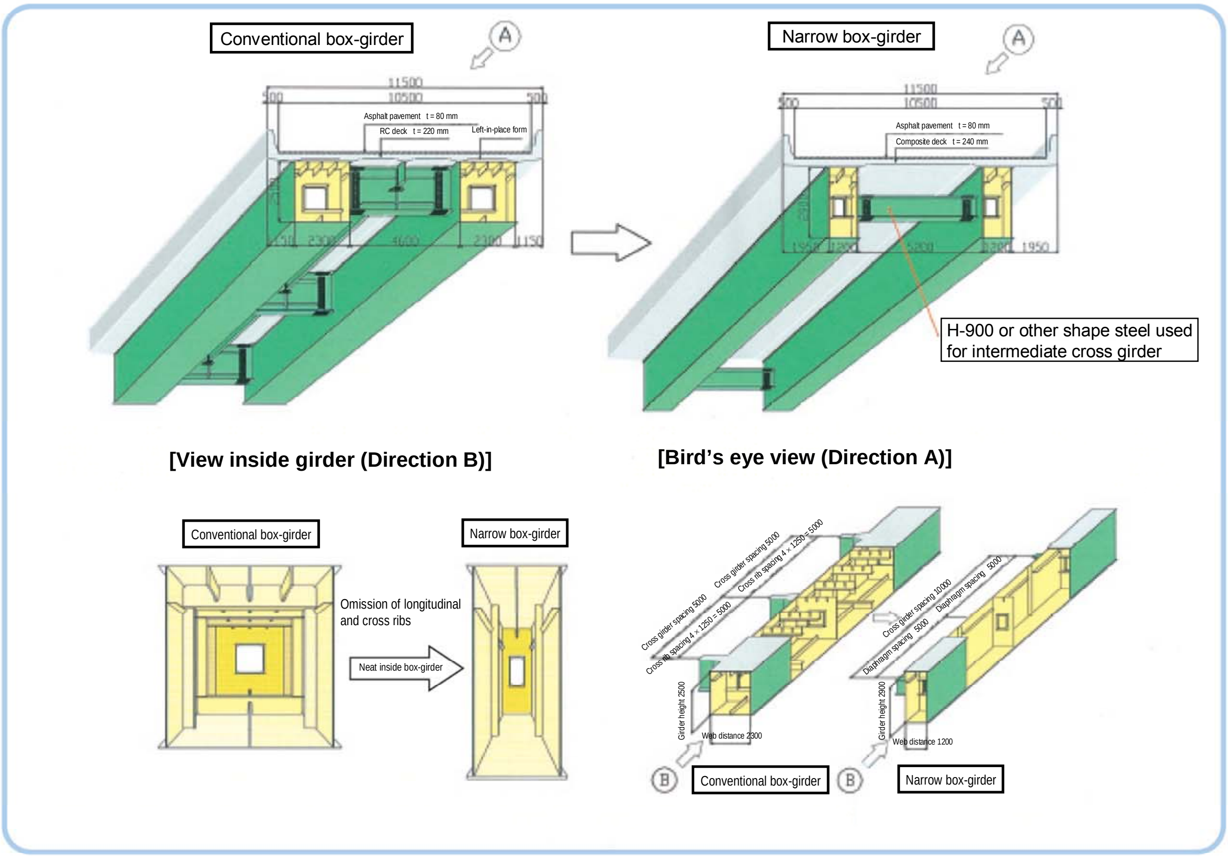


Figure 1. Structural outline of steel narrow box-girder bridge

With a rationalized bridge, the torsional rigidity and structural damping are small compared to a conventional steel girder bridge, so attention must be paid to the evaluation of aerodynamic stability. When dealing with aerodynamic stability, the evaluation of vibration characteristics and aerodynamic characteristics is important. No systematic study has been conducted on aerodynamic stability for steel narrow box-girder bridges yet, and current understanding on basic vibration and aerodynamic characteristics is insufficient.

This study was aimed at gaining an understanding of the basic vibration and aerodynamic characteristics of a steel narrow box-girder bridge and in order to do so a vibration test[1)] using an actual bridge and wind tunnel test[2), 3)] using a two-dimensional section model were conducted. The actual bridge vibration test was conducted on a three-span continuous steel narrow box-girder bridge with a maximum span length of 110 meters. Exciters were used in a steady-state excitation test and damped free vibration test to measure the natural frequency and structural damping. The wind tunnel test was conducted on two sections with aspect ratios of B/D = 2.6 and 3.4 (B: width, D: height) to investigate the effects of flow angle of attack, structural damping and turbulent flow on the aerodynamic characteristics.

2. VIBRATION TEST USING AN ACTUAL BRIDGE

It is important to evaluate the natural frequency, structural damping and other vibration characteristics when dealing with aerodynamic stability. For the steel narrow box-girder bridge, however, there have so far been very few cases of using exciters to examine the vibration characteristics in an experimental way. Thus, a vibration test using exciters was conducted on an actual steel narrow box-girder bridge with a maximum span length of 110 meters to ascertain the natural frequency, structural damping and other vibration characteristics.

2.1 Test method

The bridge in question is a three-span continuous steel narrow box-girder bridge with a bridge length of 244 meters, width of 16.15 meters and maximum span length of 110 meters (Figure 2). For the bearings, a seismic force distributing natural rubber bearing was employed and the bridge surface was not paved when the vibration test was performed.

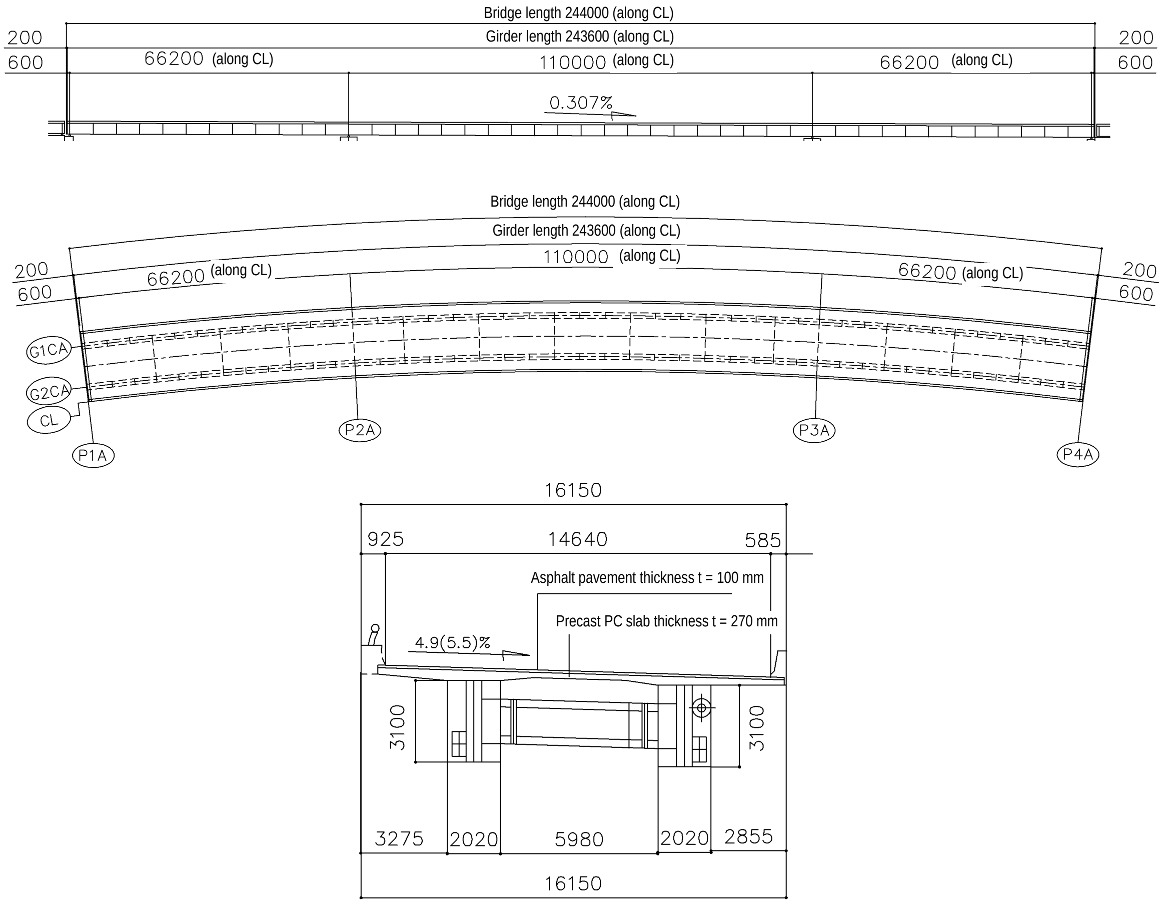


Figure 2. Continuous 3-span steel narrow box-girder bridge

For the vibration test, two exciters (0.1 to 2 Hz, exciting force: 120 kN per unit) were placed in the center of the center span (Figure 3), and two vibration modes, the first vertical bending mode and first torsional mode, were used. The vibration of the main girder was measured by 10 servo accelerometers installed on the bridge surface. Eight laser displacement meters were installed on the rubber bearings on intermediate supports to check the behavior of the rubber bearings. During the measurement, the signals from the servo accelerometers and laser displacement meters (layout drawing, Figure 4) and the control signal data to the exciters were sampled simultaneously, and time-series data processing was performed to display the vibration measurement condition on a personal computer in real time. An outline of the measurement and analysis system is shown in Figure 5.

Figure 3. View of exciter installation

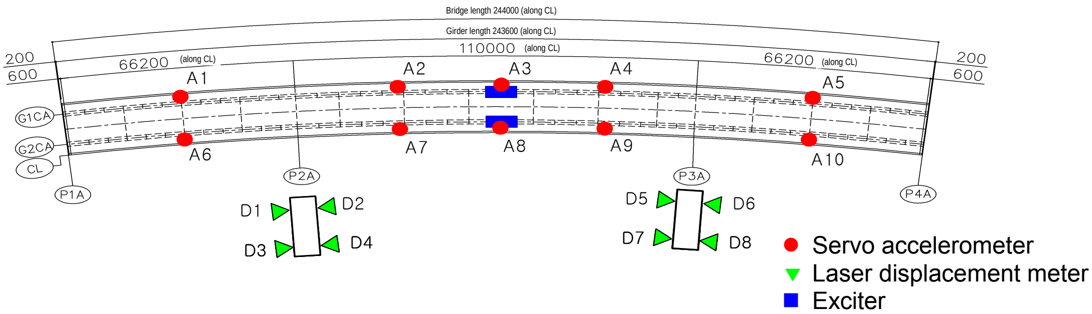


Figure 4. Measuring instrument layout

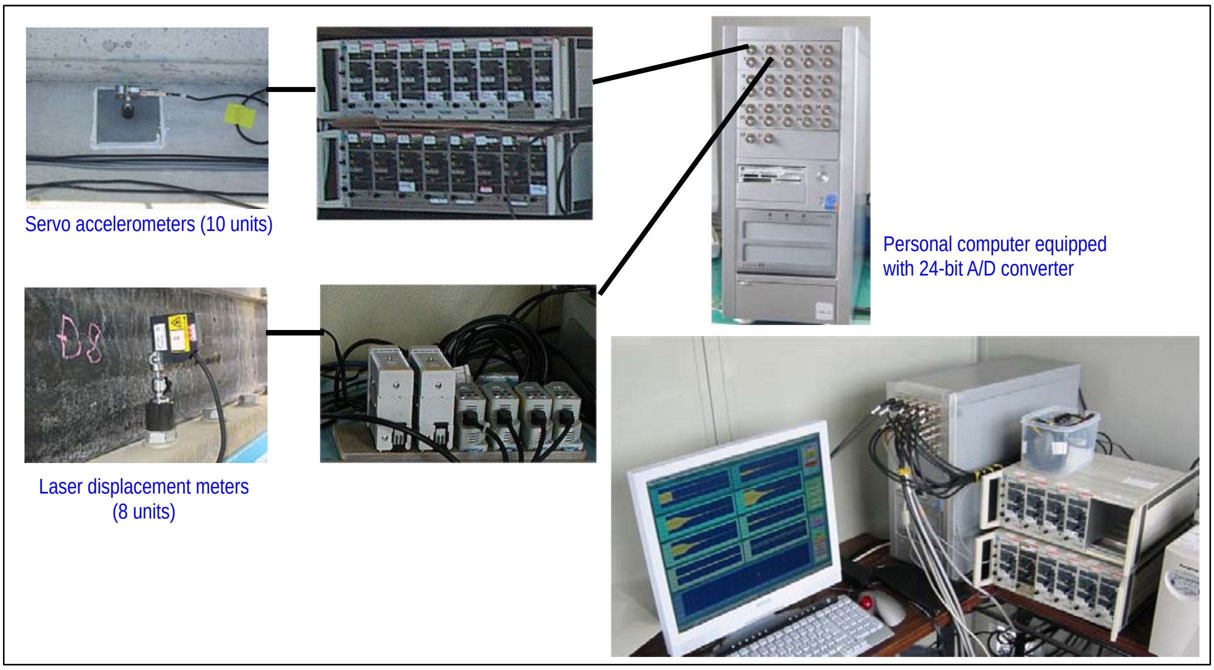


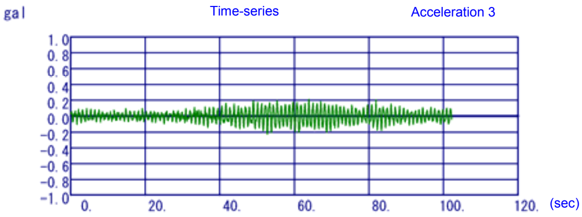
Figure 5. Outline of measurement and analysis system

The test included observation of ambient vibration, steady-state excitation test and damped free vibration test. The observation of ambient vibration was for determining the excitation frequency range of the exciters, and the observation of ambient vibration was observed by the servo accelerometers installed on the slab. The steady-state excitation test was for searching for the natural frequency of the main girder. The natural frequency was estimated from the observation of ambient vibration for each vibration mode and the excitation frequency of the exciters was swept over the range within about 20 percent of the estimated natural frequency to obtain a resonance curve. The damped free vibration test was for searching for the structural damping factor at the natural frequency of the main girder. When the amplitude of vibration excited by the exciters reaches a steady state, the exciters are suddenly stopped to obtain a damped vibration. Then the natural frequency and structural damping factor can be found from this data.

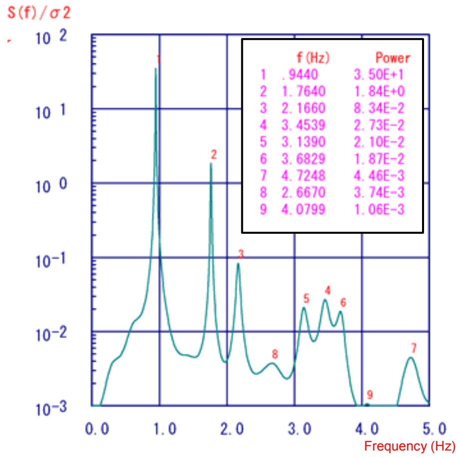
2.2 Test results

(1) Observation of ambient vibration

The time-series and power spectrum obtained by observation of ambient vibration are shown in Figure 6. The object of measurement can be found from the results of observation of ambient vibration, that is, the natural frequency of the first vertical bending mode can be estimated at f_h = 0.95 Hz or so and the natural frequency of the first torsional mode at f_θ = 1.76 Hz or so.



(a) Time-series

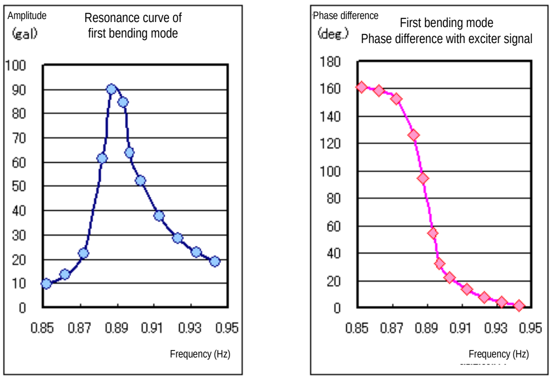


(b) Power spectrum

Figure 6. Results of observation of ambient vibration

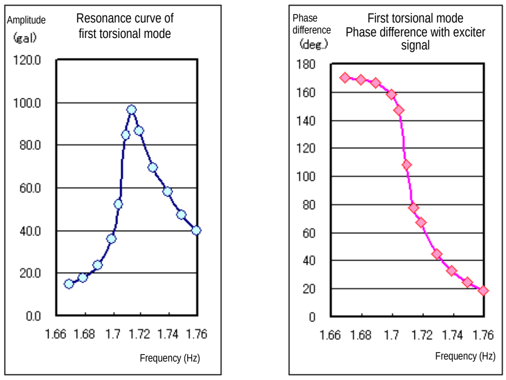
(2) Steady-state excitation test

A steady-state vibration test was performed with the amplitude of the exciter control signal kept constant while only changing the excitation frequency, to obtain the amplitude of the accelerometers on the main girder and the phase difference of the exciter control signal along with the resonance curve. The measurement results of the steady-state excitation test for the first vertical bending mode and first torsional mode are shown in Figures 7 and 8, respectively. The resonant frequency of the first vertical bending mode was found to be f_h = 0.89 Hz and that of the first torsional mode was found to be f_θ = 1.71 Hz. The frequency ratio of the first torsional mode to the first vertical bending mode was f_θ/f_h = 1.92. These results were compared with the results of an eigen value analysis using a space frame model. The comparison in natural frequency is shown in Table 1 and the comparison in vibration mode shape is shown in Figure 9. Looking at both the first vertical bending mode and first torsional mode, it can be seen that the measured values of natural frequency and vibration mode shape agree well with the results of the eigen value analysis.



(a) Resonance curve (b) Phase characteristics

Figure 7. Results of steady-state excitation test (First vertical bending mode)

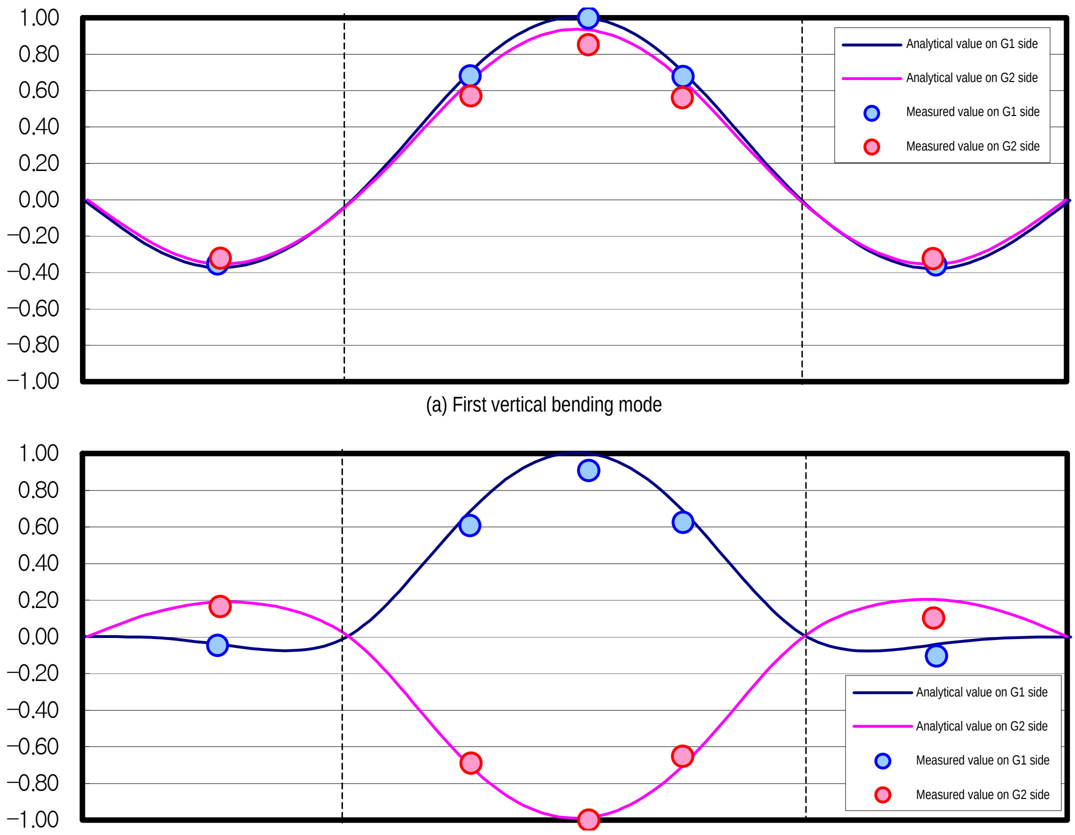


(a) Resonance curve (b) Phase characteristics

Figure 8. Results of steady-state excitation test (First torsional mode)

Table 1. Comparison of natural frequency with analytical values

Vibration mode	Measured value ①	Analytical value ②	Ratio ①／②
First vertical bending f_h	0.89 Hz	0.885 Hz	1.006
First torsional f_θ	1.71 Hz	1.724 Hz	0.992
Frequency ratio f_θ / f_h	1.92	1.948	0.986



(a) First vertical bending mode

(b) First torsional mode

Figure 9. Vibration mode shape and comparison with analytical values

(3) Damped free vibration test

The time-series measured by the damped free vibration test is shown in Figure 10. To obtain the logarithmic decrement, the damped free vibration was passed through a band-pass filter for noise removal and the logarithmic decrement value was calculated for each amplitude. The relationship between logarithmic decrement and amplitude is shown in Figure 11. In the small amplitude region, the dependence of logarithmic decrement on amplitude is seen to be high. According to the Wind Resistant Design Manual of Road Bridges [4)], no combination of repetition rate and induced stress for degrees of vibration that would produce acceleration levels up to 100 gal will reach a level at which a risk of fatigue failure is judged to exist. Thus, for the structural damping used in evaluating aerodynamic stability, it is believed to be appropriate to calculate its value as a logarithmic decrement at a somewhat large amplitude (100 gal).

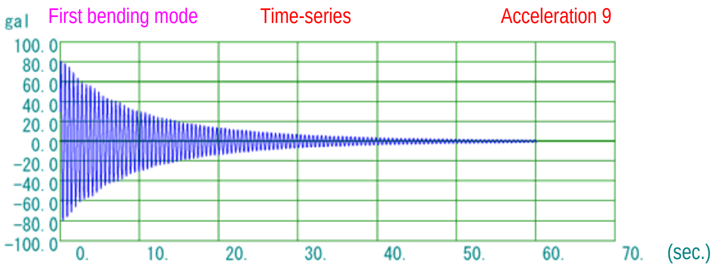


Figure 10. Damped free vibration

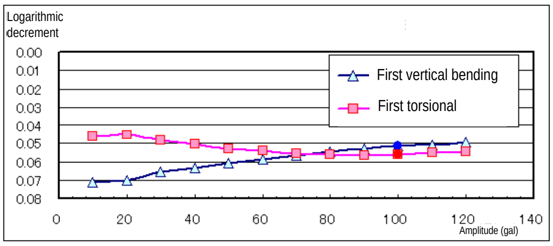


Figure 11. Dependence of logarithmic decrement on amplitude

The logarithmic decrement at about 100 gal was found from the damped free vibration test results, namely, that the first vertical bending mode was δ_h = 0.051 and that the first torsional mode was δ_θ = 0.056.

During the vibration test, the behavior of the rubber bearing was measured. As a result, it was confirmed that the longitudinal and rotational displacements of the rubber bearing were very small and, for large amplitudes around 100 gal, they mostly agreed with the analytical displacement values.

3. WIND TUNNEL TEST

It is important to evaluate aerodynamic characteristics when dealing with aerodynamic stability. For steel narrow box-girder bridges, however, even basic aerodynamic characteristics are not fully understood.

Thus, a wind tunnel test was conducted using a two-dimensional section model of a steel narrow box-girder bridge to examine the effects of flow angle of attack, structural damping (logarithmic decrement) and turbulence on aerodynamic characteristics.

3.1 Test method

The wind tunnel test assumed the two three-span continuous steel narrow box-girder bridges shown in Figure 12. The bridge A has a width of 11.5 meters while the bridge B is 16 meters wide. They differ in cross-sectional aspect ratio B/D, namely, B/D = 2.6 for the bridge A and B/D = 3.4 for the bridge B. The wind tunnel test models are two-dimensional section models made to a scale of 1/40 (for bridge A) and to a scale of 1/45 (for bridge B). The various model dimensions are shown in Table 2 and a view of the tunnel test is shown in Figure 13. In the wind tunnel test, a response test was performed first in a smooth flow with the angle of attack set to α = -3, 0 and +3 degrees to examine the

effect of flow angle of attack. To examine the effect of the structural damping of the steel narrow box-girder bridge, a response test was performed with the angle of attack set to α = 0 degrees and the structural damping varied from δ = 0.03 to 0.06. Then, generating two kinds of grid turbulence in the wind tunnel, a response test in a turbulent flow was performed with the angle of attack set to α = 0 degrees and the structural damping set to δ = 0.03 and 0.04. The turbulence was generated by a grid turbulence installed upstream in the wind course and two levels of turbulence intensity were used, a low turbulence of approximately Iu = 5 % and a high turbulence of approximately Iu = 10%.

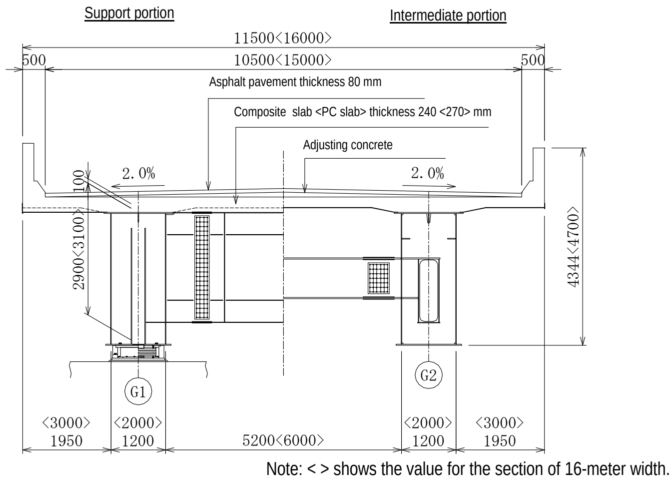


Figure 12. Bridge section under consideration

Table 2. Dimensions of model

	Bridge A (11.5 meters wide)		Bridge B (16 meters wide)	
	Actual bridge	Model	Actual bridge	Model
Scale	1/40		1/45	
Maximum span length	80m		110m	
Width (B)	11.5m	287.5mm	16.0m	355.6mm
Representative height (D)	4.344m	108.6mm	4.700m	104.4mm
Cross-sectional aspect ratio (B/D)	2.6	2.6	3.4	3.4
Main girder height	2.9m	72.5mm	3.1m	68.9mm
Unit weight	163kN/m	101N/m	248kN/m	123N/m
Polar moment of inertia	228 $kN \cdot s^2 \cdot m/m$	0.0887 $N \cdot s^2 \cdot m/m$	391 $kN \cdot s^2 \cdot m/m$	0.0953 $N \cdot s^2 \cdot m/m$
Vertical bending frequency (f_h)	1.17Hz	3.03Hz	0.89Hz	2.75Hz
Torsional frequency (f_θ)	2.28Hz	5.90Hz	1.72Hz	5.32Hz
Frequency ratio (f_θ/f_h)	1.95	1.95	1.93	1.93

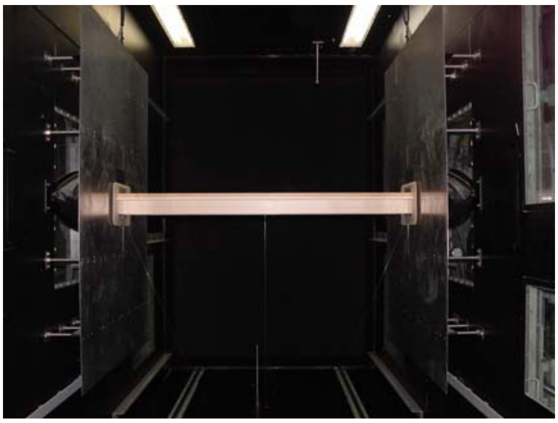
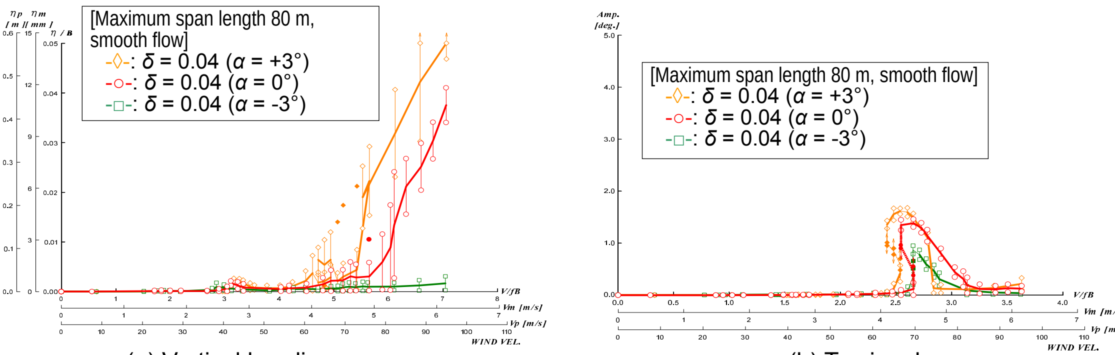


Figure 13. View of wind tunnel test

3.2 Test results

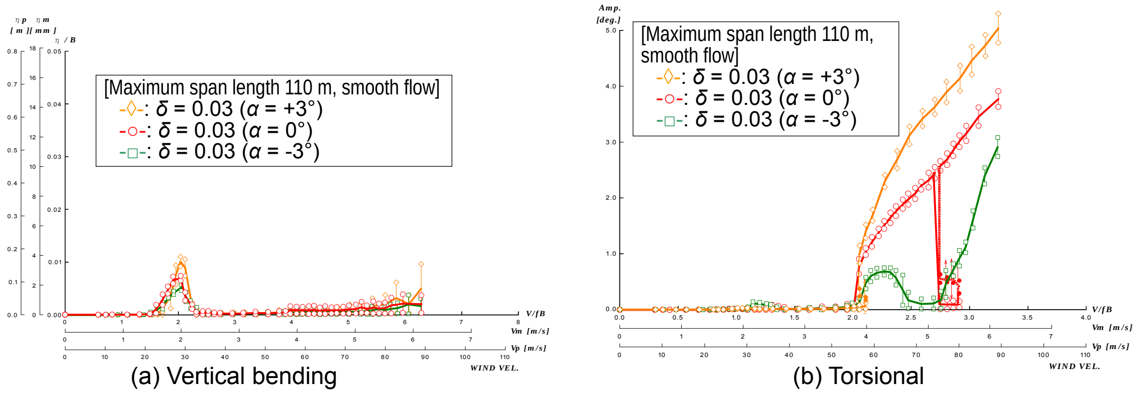
(1) Effect of flow angle of attack

A response test was performed in a smooth flow with structural damping set to δ = 0.03 and 0.04 and the angle of attack set to α = -3, 0 and +3 degrees. The response test was performed for vertical bending vibration and torsional vibration at the different air flow angles of attack, and the results are shown in Figures 14 and 15. V is wind speed, f is the natural frequency of vertical bending vibration or torsional vibration, and B is the overall width of the slab.



(a) Vertical bending (b) Torsional

Figure 14. Aerodynamic response (Effect of angle of attack for bridge A)



(a) Vertical bending (b) Torsional

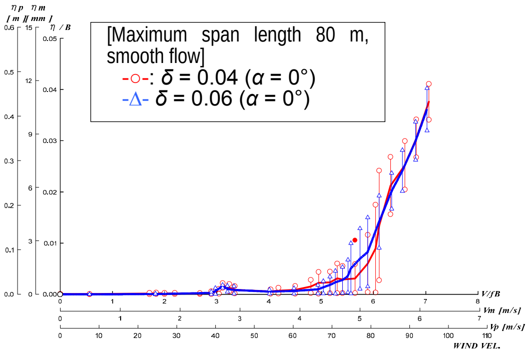
Figure 15. Aerodynamic response (Effect of angle of attack for bridge B)

With regard to vertical bending vibration, the occurrence of galloping was confirmed for bridge A in the high wind speed region while bridge B was stable with respect to galloping. For bridge B, vortex induced vibration occurred near a dimensionless wind speed of V/fB = 2. Vortex induced vibration of torsion occurred with both bridges; however, for bridge B, it was confirmed that it made a direct transition to torsional flutter at α = 0 and 3 degrees and δ = 0.03.

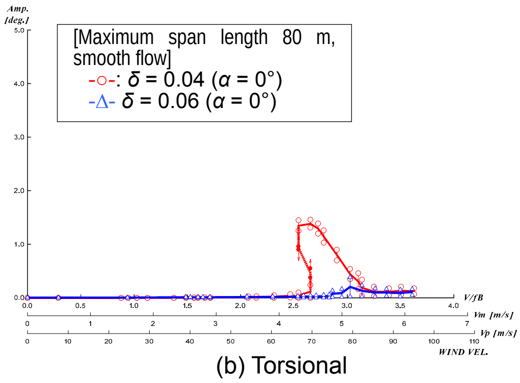
One of the effects of the angle of attack was that the response amplitude of vortex induced vibration tended to decrease at α = -3 degrees and to increase at α = +3 degrees for either cross-sectional aspect ratio.

(2) Effects of structural damping

A response test was performed in a smooth flow with the angle of attack set to α = 0 degrees and structural damping (logarithmic decrement) varied from δ = 0.03 to 0.06. The response test was performed for vertical bending vibration and torsional vibration at the different levels of structural damping and the results are shown in Figures 16 and 17.

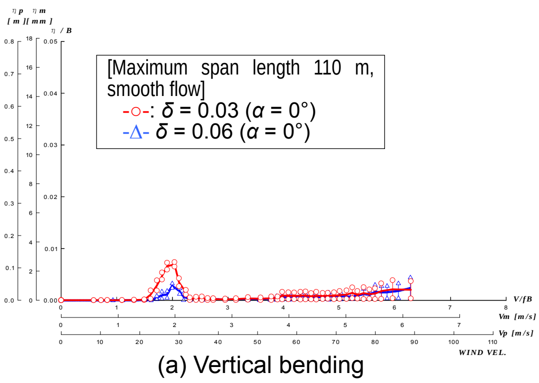


(a) Vertical bending

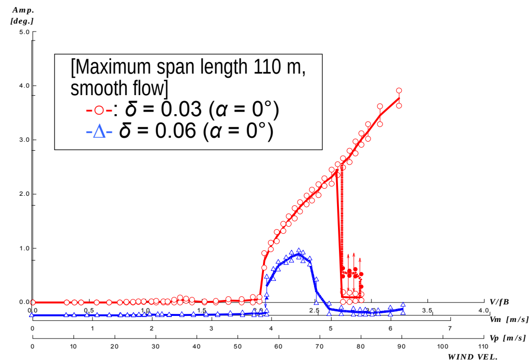


(b) Torsional

Figure 16. Aerodynamic response (Effect of structural damping for bridge A)



(a) Vertical bending



(b) Torsional

Figure 17. Aerodynamic response (Effect of structural damping for bridge B)

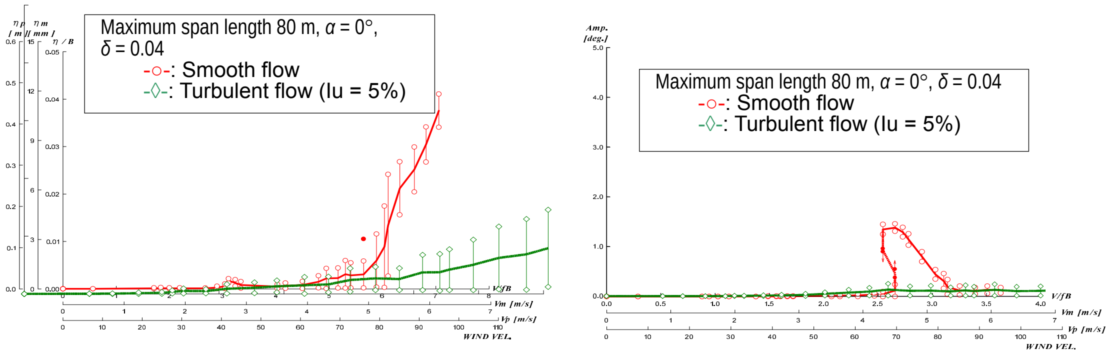
In terms of vertical bending vibration for bridge A, in which galloping occurred in the high wind speed region, little effect of structural damping was seen. However, bridge B, in which vortex induced vibration occurred in the low wind speed region, the excitation-inducing amplitude was confirmed to decrease with increasing structural damping.

With regard to torsional vibration, it can be seen that vortex induced vibration almost disappears with increasing structural damping for bridge A. For bridge B it was confirmed that the flutter at dimensionless wind speeds of V/fB = 2.7 or higher was separated and stabilized with increasing structural damping and vortex induced vibration alone occurred.

The effect of structural damping on aerodynamic response shows up more noticeably in torsional vibration, so the setting of structural damping is important for rational aerodynamic stability design.

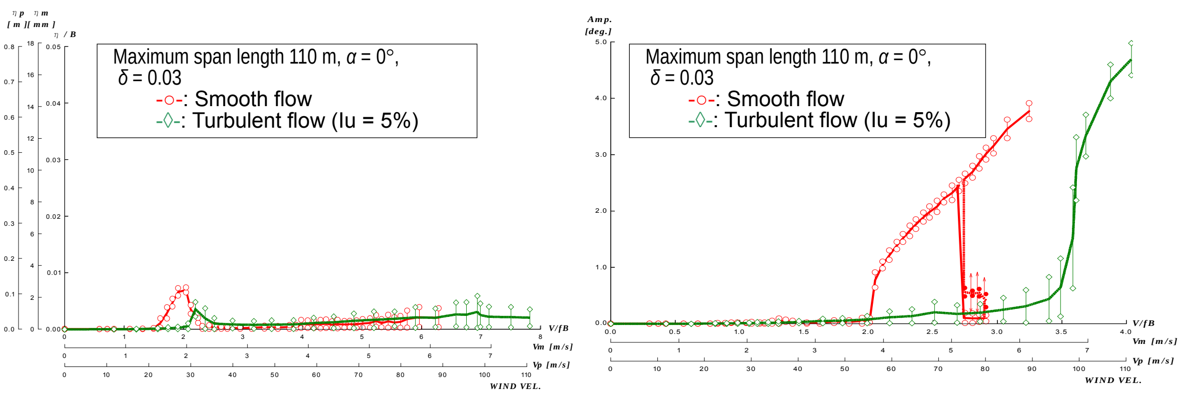
(3) Effect of turbulence

A response test was performed with the angle of attack set to α = 0 degrees and structural damping set to δ = 0.03 and 0.04 while generating two kinds of turbulence in the wind tunnel. The response test was performed in a turbulent flow for vertical bending vibration and torsional vibration and the results are shown in Figures 18 and 19. In these figures, the aerodynamic response in a smooth flow is also shown for comparison.



(a) Vertical bending (b) Torsional

Figure 18. Aerodynamic response (Effect of turbulence for bridge A)



(a) Vertical bending (b) Torsional

Figure 19. Aerodynamic response (Effect of turbulence for bridge B)

Paying attention to vortex induced vibration, it can be seen that it has almost disappeared by the low turbulence of Iu = 5% for both bridges A and B. Paying attention to galloping and flutter, the galloping that had occurred in bridge A was stabilized in the turbulent flow and only a gust response was observed. It was found that the flutter-inducing wind speed of bridge B shifted to V/fB = 3.5, which is well within the high wind speed region. It was confirmed that either section was stabilized by turbulence with respect to vortex induced vibration, galloping and flutter.

4. CONCLUSIONS

The vibration and aerodynamic characteristics of a steel narrow box-girder bridge are important in evaluating its aerodynamic stability. To understand these characteristics, a vibration test was performed using a actual bridge and a wind tunnel test was conducted using a two-dimensional section model. Major findings obtained are as follows:

1) For the steel narrow box-girder bridge, its natural frequency of the first torsional mode tends to be low because its torsional rigidity is lower than a conventional ordinary steel box-girder bridge. The frequency ratio of the first torsional mode to the vertical bending mode was f_θ/f_h = 1.92.

2) For the steel narrow box-girder bridge with a maximum span length of 110 meters, its structural damping was δ_h = 0.051 for the first vertical bending mode and δ_θ = 0.056 for the first torsional mode. However, structural damping is noticeably dependent on amplitude. Thus, for the structural damping used in evaluating aerodynamic stability, it is believed to be appropriate to calculate its value as a logarithmic decrement at a somewhat large amplitude (for 100 gal).

3) Of the aerodynamic characteristics of a steel narrow box-girder bridge, the response characteristics differ for different cross-sectional aspect ratios. Specifically, for a cross-sectional aspect ratio of B/D = 3.4, a tendency to become unstable to torsional vibration was observed. For both sections with aspect ratios of B/D = 2.6 and 3.4, it was found that the turbulence effect could well be expected and the aerodynamic stability was markedly improved in a low turbulent flow of a turbulence intensity of approximately Iu = 5%.

The wind resistance of steel bridges is influenced by the wind and vibration characteristics at the bridge site, presence or absence of noise barriers and juxtaposed bridges and other variable conditions. Future studies on the wind resistance of steel bridges, including variations in these conditions are necessary.

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